Lombard (W. P.)
and Pillsbury (W. B.) al

Reprinted from the American Journal of Physiology.
VOL. III.—DECEMBER 1, 1899.—NO. V.

A NEW FORM OF PISTON RECORDER AND SOME OF THE CHANGES OF THE VOLUME OF THE FINGER WHICH IT RECORDS.

presented

BY WARREN P. LOMBARD AND W. B. PILLSBURY.

[FROM THE PHYSIOLOGICAL LABORATORY OF THE UNIVERSITY OF MICHIGAN.]

With the Compliments
of
Dr. Warren P. Lombard.
and
W. B. Pillsbury

805 Oxford St. Ann Arbor, Mich.

A NEW FORM OF PISTON RECORDER AND SOME OF THE CHANGES OF THE VOLUME OF THE FINGER WHICH IT RECORDS.

By WARREN P. LOMBARD and W. B. PILLSBURY.

[*From the Physiological Laboratory of the University of M*

OF the many forms of apparatus which have been devised for recording small changes in volume of members or organs of the animal body, the most delicate is Ellis's piston recorder.[1] This instrument gave good results in the hands of its ingenious inventor, but was so fragile that it has never come into general use. It consisted of a glass tube, containing a piston of paraffin connected by a straw piston rod with a lever of straw and paper. The piston was turned almost to fit the tube, the intervening space being filled with a volatile oil, such as oil of peppermint or cloves. The fact that the oil tended to dissolve the paraffin was considered an advantage, as it caused a more complete union between them and helped to secure an air-tight closure of the tube. Ellis chose air in preference to water or oil as a medium for transmitting the changes in volume; in part, because air is not liable to the oscillations which are seen in a column of liquid when suddenly moved, and, in part, because air can be employed without subjecting the organ to be studied to external changes in pressure. Since air is easily compressed, it was necessary that his recording apparatus should offer the least possible resistance to the movement of the air; he therefore constructed it of the lightest materials, and sought to avoid every form of friction.

Several investigators [2] have described more or less modified forms of Ellis's instrument, and Hürthle,[3] in his excellent article on transmission of pressures by air, recounts a series of experiments made to ascertain the best form of piston recorder, and its efficiency as compared with the recording tambour. The form which he found to give

[1] Ellis, F. W.: Journal of physiology, 1886, vii, p. 309.

[2] Johansson and Tigerstedt: Skandinavisches Archiv für Physiologie, 1889, i, p. 345; Schäfer, E. A.: Journal of physiology, 1884, v, p. 130.

[3] Hürthle: Archiv f. d. ges. Physiol., 1893, liii, p. 301.

the most accurate results, and which he states to be the best instrument thus far devised for recording air waves, was considerably lighter than that used by Johansson and Tigerstedt, the total weight of the movable parts being only 0.68 gram. Although heavier than the form employed by Ellis, it had the advantage of durability.

The writers of this paper, having become interested in a line of work which required an accurate record of very slight changes in volume, found it necessary to employ Ellis's method, and to give to his instrument a more permanent form. Not being at the time aware of Hürthle's results, they made many of the experiments which he describes, and are able to corroborate his conclusions as to the construction of a delicate and accurate piston recorder. The piston must be thin, to minimize the friction in the tube; it must be of small diameter and be connected by a joint with the piston rod and the lever, so that it shall not tilt and bind; the movable parts must be as light as possible, to avoid the effects of inertia and momentum. The instrument to be described meets these requirements. Moreover, the movable parts have but one half the weight of those of Hürthle's apparatus, namely, 0.34 gram. The greatest difficulty to be overcome in devising such an instrument lay in the necessity of having the piston rod connected with the piston by a light ball and socket joint. The piston must move freely in the tube, and yet follow readily the movements of the lever. Not only does the lever describe an arc as it moves up and down, but if it has the flexibility essential to prevent friction on the drum surface, it may readily be displaced a little to one side or the other, so as not to be exactly over the centre of the piston chamber. A simple hinge-joint, such as Jaquet used in his form of piston recorder, is not sufficient to ensure that the piston shall not bind, and, because of the increased friction, fail to respond to delicate changes in volume. This difficulty was overcome by the following device.

A cylinder of plaster of Paris was cast, and then turned on a lathe to fit, but not too closely, a selected glass tube of about four mm. bore, which was to be used as the piston barrel. A depression was then bored in the exact centre of the end of this cylinder to a depth slightly greater than the diameter of the round head of a fine Carlsbad insect pin, no. 2, with a head of a little less than 1 mm. diameter and a shaft $\frac{1}{3}$ mm. thick; this was to be used as the piston rod. From the end of the cylinder, thus prepared, a disk was cut, which was as thin as could be made and not be perforated by the hole

which had been bored to receive the head of the pin. The thickness of the disk was $1\frac{1}{4}$ mm. To connect the pin piston rod by a ball and socket joint with this disk which was to serve as a piston, the disk was put on the table, the pin was placed vertically over it with its head in the hole, (see Fig. 1), a drop of water was placed in the hole, and plaster of Paris was added to it, care being taken that the plaster did not spill down on the sides of the disk. When the plaster had set and before it had hardened, the pin, which was still pressed firmly into the hole, was given a rotary motion, so that the head should form a suitable socket for itself, and this movement was repeated from time to time until the plaster had hardened. This piston with its rod, because of its lightness and the presence of the joint, proved more durable than might have been supposed, and was able to resist much abuse. The one employed by us at present has been in almost daily use for several months. The petroleum oil which was used to lubricate the piston, seemed to harden the plaster.

FIGURE 1. The piston and piston rod slightly enlarged.

It has been found that a piston with a ball and socket joint, almost as light and perhaps even stronger than that just described, can be made by turning out a light disk of ivory, hollowing it to form a thin walled cup, perforating the bottom of the cup with a hole the size of the insect pin to be used as the piston rod, bevelling both edges of the hole, and, finally, after putting the pin through the hole so that the head lies in the bottom of the cup, filling the cup with plaster of Paris. In this case, also, as the plaster hardens, the pin should be given a rotary movement and be allowed to form a socket for itself. A little plaster disk of this kind, connected with a light long pin by a ball and socket joint, may find a number of uses; for example, it is a convenient means of connecting a frog's heart with a recording lever.

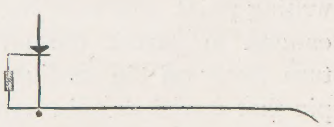

FIGURE 2. The lever. One half actual size.

The lever of the piston recorder should be very light, in order that it shall not oppose the movements of the piston by its inertia, nor exaggerate them by acquiring momentum. This is absolutely indispensable, for the piston rests on a column of air in the tube, as Ellis says, as on a delicate spring. Further, the compressibility of the medium by which it is propelled, requires that it shall write on the

recording surface with the least possible friction; it must, therefore, be flexible, so as to yield to the inequalities in the recording surface and at the same time be sufficiently springy to maintain a continuous, gentle pressure on the recording surface. Finally, although yielding readily to pressure applied horizontally it must be unyielding in the vertical direction, so that it may give an accurate record of the movements to which it is subjected.

Having these requirements in mind, we constructed the lever as follows. A strip of phosphor-bronze, 0.06 mm. thick, $2\frac{1}{2}$ mm. wide, and 100 mm. long, was shaped at one extremity to form a sharp writing point; the other end of the strip was then bent twice at right angles upon itself, and the pin, which was to serve as the axis of the lever, was passed through holes bored in the shaft of the lever and in the end of the strip which had been bent parallel to it (see Fig. 2). The first bend was 82 mm. from the writing point, the second 11 mm. from the first. The holes for the axis were bored 76 mm. from the writing point, and were just large enough to permit the lever to turn freely on the medium sized pin that served as axis. Another smaller hole was bored through the shaft of the lever, $8\frac{1}{2}$ mm. from the axis, to form the bearing of the piston rod. This caused the movements of the piston to be magnified about nine times. The piston rod pin was bent at right angles 12 mm. from the piston, and then passed through the hole which had been prepared for it in the shaft of the lever. It was prevented from falling out by a second sharp upward bend (see Fig. 1).

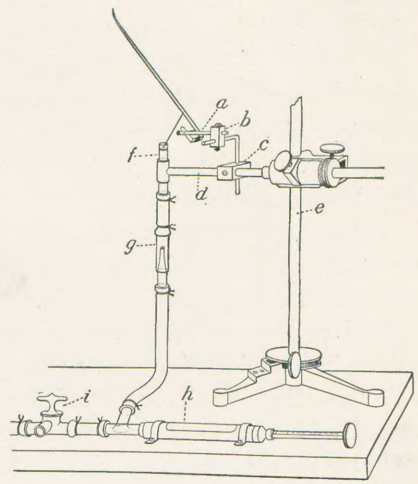

FIGURE 3. The piston recorder and its connections. One fourth the actual size.

After the piston rod was attached to the lever, a drop of petroleum oil was put on the plaster of Paris piston, and then a bit of lead, which exactly sufficed to counterbalance the lever and moistened piston, was clamped on the horizontal back plate. The total weight of the counterbalanced lever, with its pin axis, piston rod, and oiled

piston, was 0.39 gram. A little cone-shaped washer of brass was put on the pin axis, with its apex towards the lever, to keep it from rubbing on the support of the axis.

The pin used as the axis of the lever was supported by being passed through a hole near the extremity of a small horizontal brass rod, (*a*, Fig. 3), and secured by a binding screw in the end of the rod. This rod was in turn supported by a little clamp, (*b*), which fastened it to the horizontal arm of an L-shaped rod, the vertical arm of which was fastened by a clamp, (*c*), to a strong horizontal rod, (*d*), which was clamped near one end to an iron standard, (*e*), and carried at the other end a socket, which held the glass tube which served as the piston barrel, (*f*). By suitable adjustment of these rods and clamps, the bearing of the piston rod could be brought directly over the centre of the glass piston barrel, so that the piston could move with the least possible friction.

The records were taken on a Ludwig kymograph-drum, covered with highly glazed, very thin paper blackened with soot. That the friction of the writing point on the recording surface may be minimized, it is essential that it shall write at a tangent to it, and in a plane parallel to that of the drum. Further, it is very important that there shall be some device for rapidly adjusting the piston recorder, so that the writing point shall barely touch the surface of the drum. Either Boehler's universal stand, Runne's Basel stand, or some similar contrivance will suffice to make this last adjustment quickly at any time during the experiment; the former we found very serviceable.

The piston barrel was connected with the rubber tube leading to the plethysmograph chamber in one of two ways, each of which prevented the oil, which spread from the piston down the wall of the barrel, from entering the rubber tube.

a. A short rubber tube connected the lower end of the piston barrel with a short glass tube, (*g*), into the lower end of which had been sealed the slightly drawn out end of a second short piece of glass tubing. The space around this drawn out end acted as a catch-basin for the oil. The lower end of the second piece of glass tubing connected with the rubber tube which communicated with the plethysmograph chamber.

b. The piston barrel was cemented into one of the short arms of a brass T-tube, which was so placed that the short arms were vertical and the longer stem horizontal. The horizontal stem was clamped

to the standard, and carried a clamp which supported the rods which held the writing lever in place. The end of the lower short arm of the T was corked and acted as the catch-basin for the oil leaking down from the barrel.

The thick walled rubber tube connecting with the piston recorder as described above did not communicate directly with the plethysmograph chamber. It connected first with a short armed T-tube, which communicated, on the one hand, with a syringe, (*h*), and on the other with a three-way stopcock (*i*).

The syringe was air-tight, and it was possible, by movement of the plunger, to alter the amount of air in the system of tubes connecting the recorder with the finger chamber. This is absolutely essential, in order that the changes of volume which are caused by temperature or by movements of the finger may be compensated, and the position of the piston recorder on the drum be adjusted. A large form of hypodermic syringe suffices; but, as very slight movements of the plunger cause large movements of the recording lever, it is best to solder the nut on the rod of the plunger to the syringe, and to move the plunger by screwing it in and out.

The three-way stopcock, (*i*), was connected not only with the piston recorder, but, by means of rubber tubing, with the plethysmograph chamber for the finger. The third opening of the stopcock communicated with the outside air. This arrangement made it possible to connect the piston recorder with the finger chamber, or either piston recorder or finger chamber with outside air. This was necessary, especially at the beginning of an experiment, when the finger was being introduced into the apparatus, and when the temperature of the air in the finger tube was changing rapidly.

Experiments showed that it is important that the temperature of the finger should be kept as far as possible constant, especially during cold weather; moreover, in certain lines of work it is desirable to change the temperature suddenly. Two forms of apparatus were employed for regulating the temperature about the finger. In the first form, the tube containing the finger was surrounded by a jacket through which water of a known constant temperature circulated. The finger tube of this double walled plethysmograph chamber was $11\frac{1}{2}$mm. long, and $2\frac{1}{2}$mm. inside diameter; and it was open at one end to receive the finger, and closed at the other by a plate which was perforated by two small brass tubes. One of these tubes was connected by a stiff-walled rubber tube with the three-way stop-

cock, and so with the piston recorder or the outside air; the other tube permitted the introduction of a thermometer into the finger-chamber.

The brass jacket through which the water circulated was a little shorter than the finger tube. The open end of the finger tube projected slightly beyond the jacket, and carried on its outside a flange which enabled the opening between the finger and the tube to be closed by a rubber membrane, sleeve, or glove finger, such as was employed by Mosso in his experiments with the sphygmomanometer. In our experiments, however, the opening between the finger and the brass tube was closed by a cork, as will be described later. A system of reservoirs and tubes permitted the finger to be subjected to a known constant temperature, and allowed the temperature surrounding it to be changed quickly to any desired degree.

The second method permitted the finger to be kept at a constant temperature, but did not allow of sudden changes of temperature. In this method the finger plethysmograph consisted of a glass tube, closed at one end by the finger cork, and at the other by a cork through which a thermometer and the glass tube connecting with the piston recorder passed. A coil of fine wire was wound many times around the glass chamber, and when an electric current was turned on, heated the chamber. The temperature was controlled by means of a rheocord, which permitted the flow of the current to be regulated. During summer weather, the room temperature is sufficiently high and constant for ordinary investigations, and these methods of heating are unnecessary. It is sufficient to enclose the finger in a test tube drawn out at one end for the attachment of the tube connecting with the piston recorder. In all cases it is necessary to protect the subject, the plethysmograph chamber, and the system of air tubes connecting the plethysmograph chamber with the recorder, from sudden changes in temperature. The whole arrangement forms a very delicate recording thermometer, and, if not guarded, may give false results. Ellis speaks of this, and in some of his experiments used a second, control apparatus. We have found that for experiments which last only a short time and are taken with suitable precautions this is unnecessary.

Method of closing the opening between the finger and the reservoir. — One of the greatest sources of error to be encountered in plethysmographic experiments arises from the fact that movements of the arm, be they caused by changes in the tension of the muscles or by some

form of movement of the trunk, as in respiration, tend to cause movements of the finger in the plethysmograph, not always to be distinguished from changes in volume of the finger. As a change of even less than $\frac{1}{2}$ cubic millimetre in volume is recorded by the piston recorder, it is evident that the utmost care must be taken to secure a constant position of the finger as respects the plethysmograph. On account of the mobility of the skin on parts beneath, the arm and hand cannot be fixed absolutely by splints, casts, etc., and if the plethysmograph chamber be fastened to a firm support it is impossible to prevent the finger from moving in the tube. To overcome this difficulty it is necessary to resort to the principle first employed by Chelius, and rediscovered by Mosso, who employed it in his arm plethysmograph, namely, the suspension of the plethysmograph chamber and the arm by a long cord, so that they will move freely and yet together. Even this method is imperfect, in case the space between the finger and the plethysmograph be closed by a rubber membrane or sleeve.

The best way to close the opening between the finger and plethysmograph tube, is to put on the finger a cork ring which exactly fits the plethysmograph tube. Such a ring, if made to fit the finger only moderately tightly, offers considerable resistance to the movement of the finger, and, if smeared with vaseline, readily gives an air-tight closure, without impeding the circulation.

Apparatus for testing the delicacy and accuracy of piston recorder. — In many of the plethysmographic records taken from the finger not only pronounced pulse curves were obtained, but these curves sometimes showed marked secondary waves, similar to those seen in ordinary sphygmographic tracings. The question of course presented itself, are the dicrotic and other waves shown in the record a true expression of changes in volume of the finger, or are they artificial, *i. e.* caused by vibration of the air or oscillations of the recording apparatus? To decide this question an apparatus was constructed which should mechanically change the volume of the air in the tube connected with the recorder, at about the rate and degree indicated by the pulse waves. A stiff brass lever was fastened firmly to a steel axis, which moved on screw bearings. The lever rested on a specially devised cam which was supported by an axis which carried a pulley driven by an electric motor. On the lever was a short pillar of brass. The pillar projected slightly into the lumen of a somewhat larger glass tube, supported just above it.

The opening of the glass tube was closed by gold beater's skin, kept flexible by being moistened with water. When the cam was revolved, the pillar moved up and down, carrying with it the loose fold of gold beater's skin, and so caused a rhythmical change in volume in the chamber of the glass tube. The upper end of the glass tube was connected by a stiff-walled rubber tube with the piston recorder, and the movements of the air column in the glass tube were recorded by the piston recorder on a kymograph-drum.

In the experimental tests made with this apparatus, to determine the effect of changes in the volume of the air in the tube upon the movement of the piston recorder, the brass lever was sometimes moved by the hand, the end of the lever being held between the thumb and forefinger, and, sometimes, by rotating the cam upon which the lever rested. These tests revealed the following facts. Slow changes in volume, even if extensive, are recorded accurately. Rapid changes in volume, if extensive, may lead to a slight throw of the lever. Changes in volume of the rate and extent of those occurring in the finger, whether caused by vasomotor, respiratory, or pulse movements, are recorded accurately. The question which most interested us, was whether the record of changes in volume as extensive and rapid as those resulting from pulse movements, would show oscillations that might be confused with the dicrotic and other secondary waves which often appear in the pulse curve obtained from the finger. A form of cam was chosen such as would give a sudden upward movement and a slow fall of the brass lever. The changes of volume recorded were somewhat more extensive than those caused by the pulse, and a rate of rotation was readily obtained by the motor which gave a more rapid change of volume than the pulse records showed. To be sure of our facts, we took two records on the same drum, the one of the artificial pulse, obtained from our testing apparatus, and the other, of the normal finger pulse. The pressure of the piston recorder lever was the same in both cases. It was found that changes in volume, which were considerably more rapid and extensive than those caused by the pulse, did not show any throw of the recording lever or any secondary oscillations, and we assured ourselves that the dicrotism and other oscillations which are recorded in the normal pulse curves from the finger, do not originate in the recording mechanism (see Fig. 4). It was found further, that if the cam of the testing apparatus was revolving at a regular rate, and the air in the apparatus was rhythmically carried forwards and backwards

by movements of the adjusting syringe, a combination curve, closely resembling the pulse and respiration curves obtained from the finger, could be produced. This makes it possible to study the effect of respiratory changes in volume upon the shape of the pulse curve, a question of importance.

Latent period of the piston recorder. — This was determined empirically to be but slightly over $\frac{1}{100}$ second, and was found quite constant for both a decrease and an increase in the volume of the air. It was tested by connecting two piston recorders, or a piston recorder and a tambour, writing on the same drum, by a stiff-walled rubber tube one metre in length, a length somewhat greater than that used in our plethysmographic experiments. If the tambour lever or the lever of one of the piston recorders was suddenly moved, the piston recorder under observation was found to start about $\frac{1}{100}$ second late, and to lag at the crest of the curve, at the most, $\frac{1}{10}$ second. This lag depended on the extent and rate of the change of volume, and was due to friction of the lever on the drum, compression of the air column, and displacement of the oil about the piston. The displacement of the oil, seen when the movements were extreme and rapid, was only momentary, as capillary force drew the oil back. This error need be feared only when the movements recorded are more rapid and extensive than those which result from ordinary changes in the volume of the finger. The figures here given apply to movements very much more rapid and extensive than those caused by the volume changes of the finger due to the pulse, etc. We concluded from our experiments that such records as are obtainable from the finger, are accurate to within $\frac{1}{100}$ second, if the

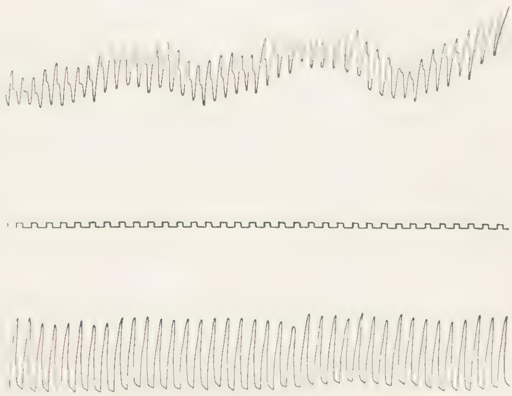

FIGURE 4. One half the original size. The uppermost curve, taken June 5, 1899, on a warm day (room temperature, 29° C.), from the two first phalanges of the left hand. The time, in seconds, is recorded at the bottom of the tracing. The lowest curve, an imitation of a pulse tracing, was obtained by using the apparatus described on page 193.

lever is adjusted properly. In this connection, however, it is necessary to express again the warning that any undue friction of the lever upon the drum is liable to delay the rate and lessen the extent of the movements of the recording lever.

Calibration of the piston recorder. — As a further test of the delicacy of the apparatus, we measured the change in the volume of the air that corresponded to the movement of the lever. To this end, movements of the lever were compared with the movements of a column of mercury in a tube of small bore, attached to the piston recorder. The volume of the tube used was ascertained first by filling the tube with mercury, and secondly, by weighing the tube when filled with mercury and when empty, and reducing from weight to volume, with suitable corrections for temperature. The results of the two methods agreed very closely. The uniformity of the bore of the tube was established by the fact that the same amount of mercury occupied equal lengths for all parts of the tube; one centimetre of the tube held 9.1 cubic millimetres of mercury. One end of this tube was connected by a rubber tube with the main tube of our apparatus, and to the other end was attached a small piece of rubber tubing filled with mercury and closed by a pinch-cock. The length of the column of mercury in the capillary tube was varied by compressing this short rubber tube between two bits of wood held in the jaws of a burette clamp. The length of the column was read on a scale and compared with the record on the drum. The result showed that a movement of one centimetre in the mercury in the tube would induce a movement of the lever of 5.7 millimetres, *i. e.*, that one millimetre on the drum corresponded to a change in volume of 1.6 cubic millimetres. Furthermore, a change of less than $\frac{1}{2}$ millimetre in the tube, or considerably less than $\frac{1}{2}$ cubic millimetre was found to produce an evident movement of the piston recorder. This also confirmed the previous results, inasmuch as different changes in the length of the column of mercury were always accompanied by relatively equal movements of the lever.

The pulse oscillations recorded in Fig. 4 bear witness to the capacity of our instrument. They were taken on a hot day, when the blood-vessels of the finger were largely dilated. This curve shows also Traube-Hering waves. The dicrotism exhibited was not due to the apparatus. In the artificial pulse shown in Fig. 4 the pulse movements were no less high and steep than those obtained from the finger, but they are free from secondary waves.

Another indication of the delicacy of the piston recorder for changes of slight intensity, was given by the fact that the capillary attraction for water in a tube with a bore of 1 mm. was strong enough to produce marked movements of the lever.

Method of class demonstrations, etc. — It is not difficult to employ the piston recorder in demonstrations before large audiences. If a small silvered cover glass be fastened in the place of the counter-balancing weight on the back of the lever, a beam of light can be thrown on a screen, and the ordinary changes in the volume of the finger caused by the pulse and respirations can be shown. The effect of reflex excitations, such as the application of ice to the skin of the other hand, may also readily be exhibited.

A Statement of some of the Facts observed with the Piston Recorder.

The account which we have given of the piston recorder was written six months ago, and since that time we have had occasion to make frequent use of the instrument. Our experience has only confirmed our opinion that the instrument, in spite of its apparent delicacy, is very durable, and with proper handling is capable of giving valuable results.

It may be of interest, as showing the value of our method, for us to enumerate some of the more salient physiological facts which have attracted our attention during our preliminary tests of this apparatus.

All of the tests were made with only two phalanges of the first or second finger of the left hand. When one of these was inserted into the plethysmograph chamber, the heat of the finger caused a rapid expansion of the air in the chamber and the system of tubes connecting it with the recorder. A considerable time was required for an equilibrium to be established between the heat of the finger and the temperature of the surrounding air. During this period of adjustment, the piston lever was kept level, either by gradually drawing out the piston of the adjusting syringe, and so enlarging the space, or by turning the three-way stopcock so as to give free communication with the outside air. As the constant rise of the piston lever due to the expansion of the air lessened, the fluctuations of the volume of the finger became evident. These volume changes were manifested by quick up-and-down movements of the lever due to the pulse, slower rhythmical movements which correspond to respiratory

movements, and much slower variations, presumably produced by vasomotor changes.

The extent of all of these fluctuations was very markedly influenced by the temperature to which the body as a whole, and more especially the finger under observation, was exposed. If the room was cold, the volume changes described were hardly perceptible, while in a warm room all three of these changes showed themselves. The difference between the size of the variations in summer and winter was very great. The general effect of the room temperature on the body could be counteracted in part by changing the temperature of the finger. When the temperature of the room was low, and the fluctuations were barely visible, it was possible to carry on experiments by raising the temperature of the air in the finger chamber to about 34°C. On the other hand, it was found that changes in volume that were fairly well marked in a moderately warm room, would become greatly lessened, or entirely disappear if the temperature of the air about the finger were lowered to about 20° C. We can confirm the results of Mosso, François-Franck, Sewall, Sanford, and others, that cold applied to the other hand noticeably decreases the volume of the finger under observation. Thus when the right hand was dipped into cold water there followed a marked shrinkage of a finger of the left hand, and the extent of the oscillations of volume due to the pulse, respiration, etc., greatly decreased.

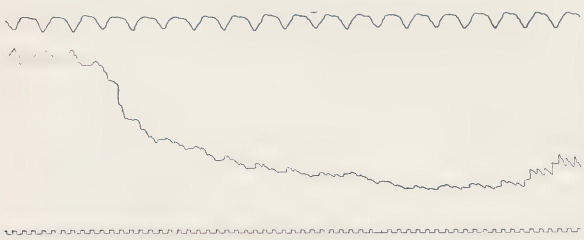

FIGURE 5. One third the original size. Plethysmographic record from two phalanges of middle finger of left hand, May 1, 1899. Height of piston lever, when horizontal, above bottom of seconds tracing = 34 mm.; height of respiration lever, when horizontal, above bottom of seconds tracing = 75 mm.; length of piston lever, 70 mm.; length of respiration lever, 93 mm. Respiration lever wrote 0.8 mm. to the right of the piston lever. Subject stated at the close of experiment that he had caught himself thinking actively of his work, and had tried to stop thinking.

Very similar results accompanied the pain caused by stimulating the skin of the other hand with an induced current. Two to three seconds after the stimulus was applied, there was a marked shrinkage of the finger, and the height of the pulse oscillations lessened.

These effects seemed to be common to nearly all the psychical and reflex disturbances that were noticed. The odor of a stale cigar held under the nose, pulling a hair, blowing in the face, and other minor persecutions, invariably gave the same result. During the progress of the experiments, the mind of the subject would very frequently drift to some problem of daily routine or one connected with the experiment. At such times the volume of the finger would show a marked fall (see Fig. 5). The only two exceptions to this rule were both at times when the mental state was one of amusement; once at a remembered event, the other time, over an incongruous conjunction of ideas in the train of thought. In these two cases a well marked and long continued rise was observed.

Sudden changes in respiration produced a very pronounced variation in the ordinary course of the experiments. A partly suppressed yawn, followed by a long expiration, for instance, was accompanied by a fall in the height of the lever. The effects of Valsalva's and Müller's experiments to cause a weakening or temporary cessation of the pulse, were, of course, at once evident.

In addition to recording changes in the circulation caused by forced respiratory movements, the instrument gave a striking picture of the normal variations in the volume of the hand when the subject was at rest. By recording the respiration with Marey's pneumograph, just over the piston recorder tracing, it was possible to notice the time relations of the movements of the wall of the chest or abdomen and the corresponding oscillations of the volume of the finger. These changes of volume were seen to hold about the same relation to the breathing movements, as has been observed for respiratory fluctuations of the blood pressure. The volume begins to increase at about the middle of inspiration, and continues to rise until about the middle of expiration; it then falls during the latter part of expiration and the beginning of inspiration. This general correspondence is, however, subject to wide fluctuations. The effects of respiration were usually shown when the volume of the finger was large. No constant relation, however, was seen to exist between the size of the pulse and the respiratory oscillations. Sometimes the pulse oscillation would be fairly large when no respiratory change was to be seen, and, at other times, there would be well marked respiratory oscillations when the pulse movements were scarcely visible.

The height of the pulse wave was very plainly influenced by the

volume of the finger. By large volumes the oscillations were relatively small, by medium they were greatest, while by small volumes they were very small or altogether disappeared. As the volume changed from large to medium, the downward oscillations were the first to increase in size and *vice versa.*

In the pulse wave the dicrotism quickly attracts attention. The dicrotism was seen to undergo marked variations, and our method bids fair to contribute important facts as to the origin of the secondary waves and the influences affecting them. A propos of the discussion as to the origin of the dicrotic wave, it is worthy of note that this wave is clearly to be seen in experiments, such as ours, which deal with the phenomena of the extreme peripheral circulation.

In addition to the pulse and respiratory changes in the volume of the finger which have been described, still another change, having a much longer period, was observed. The duration of these longer waves was from seven to ten seconds from crest to crest, which makes it probable that they were of the same type as the Traube-Hering blood pressure waves.

Still another series of facts exhibited by our tracings relate to the periodic changes in the rate of the heart. The pulse rate was found to vary with the respiration. It was higher during the latter part of expiration, and lower during inspiration. Moreover, in some cases, when the breathing was suspended, this rhythmic change in the beat of the heart showed a tendency to persist. Still another rhythmic change in the rate of the pulse, recurring in longer periods, was noticed at times.

The facts which we have here stated may suffice to indicate the value of the piston recorder, not only as a means of demonstrating many important circulatory phenomena but as giving to the plethysmographic method an added delicacy.